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Network-Optimized Design of a Notional Hybrid Electric Airplane for Thin-Haul Operations

Colby J. Weit*, Cedric Y. Justin†, and Dimitri N. Mavris‡
Aerospace Systems Design Laboratory, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, USA

Electric propulsion for aviation applications has gained significant momentum in the past few years owing to a convergence of technologies enabling the design of competitive aircraft. This excitement also highlights the expectations for how electrification enables novel airplane architectures and powertrains leading to significant reductions in energy usage, emissions, and ultimately operating costs. Thin-haul operations is a natural application for electric propulsion owing to the relatively short flights mitigating the need for large batteries. Hybridization of electric airplanes further mitigates the need for large batteries and enables an earlier entry into service. Aircraft designs often have capabilities that significantly exceed the needs of many missions making up their day-to-day operations. This study considers the optimization of a hybrid-electric aircraft for thin-haul operations and investigates how the airplane design can be modularized to enable a multi-design-point optimization. This allows the vehicle to operate as close as possible to its many design points. The objective is to maximize the aircraft direct operating profit by optimizing the hybridization ratio while accounting for the ability to trade payload for additional range. The analysis is then applied over a wide range of routes representative of the network of a thin-haul operator. This yields a network-optimized vehicle that maximizes direct operating profits. This aircraft is then compared to a baseline turboprop aircraft. Depending on the number of routes operated and profit margins being sought, the resulting design exhibits optimal hybridization ratios ranging nominally from 52% to 96%. The study also investigates the opportunity to trade payload for additional range by swapping some payload for additional batteries. The impact of various levels of battery specific energy densities on operating economics are also studied.

I. Introduction

Electric airplanes have received a significant amount of media exposure and investments in the past few years as their potential benefits are explored. Established and new companies alike have invested significantly in these vehicles [1–6]. These compelling designs are enabled by the convergence of many new technologies enabling novel vehicle configurations, higher powertrain efficiency, as well as reduced energy usage and emissions. Past studies have highlighted between 20 and 50% reduction in energy usage for a similar flight compared to a baseline fuel-burning operation [7, 8]. Coupling the energy savings with the lower cost of electric energy results in significant reduction in energy expenditures during operations. While gas turbine engine energy conversion efficiency is close to 30%, component efficiencies of an electric powertrain now exceed 90% [9, 10]. The scalability of electric components also enables new configurations and novel airplane architectures that historical monolithic propulsion systems did not allow [11].

Despite these benefits, electric aircraft concepts still face many challenges. Some of the challenges include power generation and management, thermal management, battery technology, energy storage and infrastructure at airports, battery charging and recharging, and vehicle operations [12]. This breadth of challenges is representative of the many additional hurdles to overcome to ready these vehicles for entry into service. In addition to these technical challenges, the public acceptance as well as the regulation and certification of these new operations remain challenging. In an effort to further the investigation of this multidisciplinary field, this study is scoped to explore some interesting aspects of an application of electrified airplanes. The rest of this paper provides a formulation of this exploration and the insights sought as a result of this work.

*Graduate Researcher, PhD Candidate, ASDL, School of Aerospace Engineering, Georgia Tech, AIAA Student Member.
†Research Engineer II, ASDL, School of Aerospace Engineering, Georgia Tech, AIAA Member.
‡S.P. Langley Distinguished Regents Professor and Director, ASDL, School of Aerospace Engineering, Georgia Tech, AIAA Fellow.

II. Problem Formulation

A. Study Objective

The aim of this study is to investigate the relationships between the design of a electrified propulsion aircraft, its intended operating environment, and the resulting economics. Thin-haul operations, which are short, regional operations up to 250nm using small-gauge aircraft limited to nine passengers and operated as commuters under CFR Part 135, have been identified as a prime candidate for initial electric airplane operations. Unfortunately, all-electric airplanes are typically range-restricted due to low specific energy density of batteries. In that regard, hybrid electric aircraft may present an advantage owing to the two sources of propulsive energy which may enable a sooner entry into service. This potential advantage has stimulated the interest for hybrid electric propulsion systems applied to thin-haul missions.

Furthermore, fully electric aircraft do not typically enable the trading of payload for additional fuel to cover longer missions. This constraint may lead to an over-design of the vehicle to satisfy the most demanding missions while adversely impacting the vehicle efficiency on less-demanding missions. A hybrid electric architecture brings back some of this flexibility by enabling the operator to choose the degree of hybridization and to choose between loading more payload or more fuel. In addition, this flexibility enables aircraft designers to move from single design-route optimization to a more encompassing network-wide optimization of the vehicle. This attribute also allows aircraft operators to fly a wider cross section of missions and to reduce overall operating costs using a modular airplane platform.

These considerations lead to the objective of executing a network-wide optimization of a hybrid electric aircraft design in order to maximize the direct operating profit of the airplane when operated on a typical thin-haul network of flights.

B. Electrified Aircraft Operations

Electric or hybrid electric airplanes are often discussed in the context of enabling new concept of operations (CONOPS), either for private or commercial use. One of these CONOPS is Urban Air Mobility (UAM). Vascik et al. defines UAM as “a set of vehicles and operational concepts proposed to provide on-demand or scheduled air transportation services within a metropolitan area” [13]. UAM is further delineated as approximately 50 nmi missions serving demand in metropolitan areas for commuter transportation and providing a solution to communities bogged down by traffic congestion. This demand is currently not served adequately as services are expensive for many customers. Recently, electric aircraft designers and potential operators have claimed that these novel aircraft can significantly reduce operating costs and enable thriving operations in those markets [14].

1. Concept of Operations

Thin-haul operations are conceptualized as an extension of urban air mobility operations. While the latter is understood not to exceed 50 nmi, thin-haul operations are regional operations reaching up to 250 nmi and connecting under-served regions and communities to major hubs or even bypassing hubs to link these under-served communities together. Because passenger volume on these routes is usually low, these flights are operated by smaller capacity aircraft. Historically, this low volume has led to high operating costs on a per-passenger basis resulting in limited appeal for these operations.

The promises of electric aircraft operations and the resulting reduction in operating expenditures may prove to be ‘game changing’. Thin-haul operations have significant advantages over traditional commercial air-carrier operations. Thin-haul operations do not require substantial supporting infrastructure, and smaller terminals without gates are typically used. Additionally, at the time of writing, these operations are not subjected to security checks, drastically improving the door-to-door travel time and experience of customers. Finally, thin-haul operations can benefit from the vast number of local, under-utilized airports that can sustain such services. The United States Department of Transportation Bureau of Transportation Statistics reported that in 2017, there were $19,655$ airports in the US, $5,104$ of which were public and yet, only 500 of these were supporting commercial operations [15]. This breadth of existing infrastructure is underutilized but could be actively served, circumventing significant traffic and congestion associated with larger, metropolitan airports. Figure 1 shows the existing network of airports around the United States on the left, with the right showing the limited usage of these airports for commercial operations.

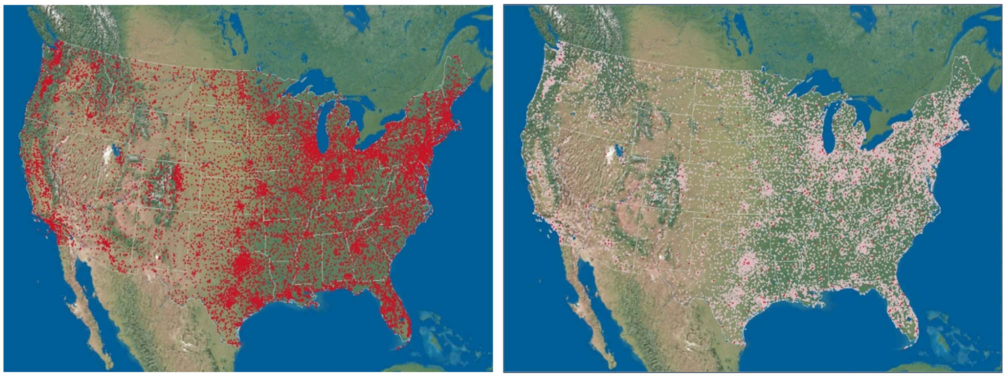

Fig. 1 Visualization of distribution of airports around the United States (left), and the small fraction of those supporting commercial operations (right)

2. Thin-Haul Network

The thin-haul network used for this study is the flight schedule of Cape Air (www.capeair.com) for an entire week of operations in August 2015. Cape Air is the largest thin-haul, commuter transport operator in the United States with over 90 aircraft in its fleet and more than 3,000 weekly flights. The distribution of flight distance within the network is shown in Fig. 2. It ranges from less than 30 nmi for the shortest routes to almost 300 nmi for the longest routes. This network constitutes a comprehensive playground for this study because of the breadth of routes served representing typical thin-haul operations.

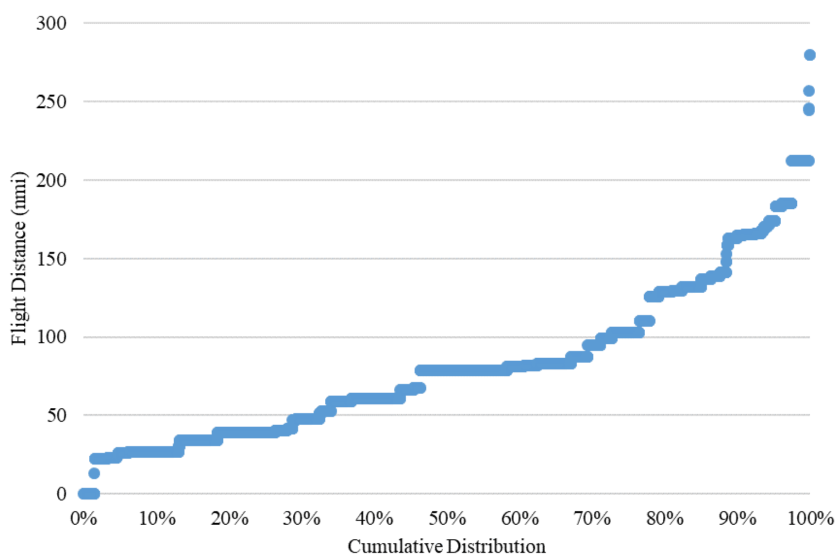

Fig. 2 Cumulative distribution of a comprehensive set of thin-haul operations

3. Vehicle Capacity

To fit within thin-haul operations, the airplanes need to meet the range and passenger requirements set forth by operators. Table 1 shows a selection of three commuter operators along with a description of the aircraft used, the seating configuration, and the maximum range of the aircraft. These aircraft have ranges that far exceed any thin-haul mission highlighted previously, supporting the inquiry of whether a modular airplane of lesser capability could have the ability to more efficiently meet the needs of operators. Additionally, a nine passengers or less capacity meets the FAA 14 CFR Part 135 requirements for operations under the commuter category, allowing for a simplification of the supporting ground and security infrastructure.

A study conducted by Kreimeier et al. explored what thin-haul operations would look like in Germany [16]. The authors accounted for feasible airfields, population density near airfields, passenger demand, passenger mode of transport, and market volume estimation. The German distribution of suitable thin-haul airfields ended up remarkably similar to the U.S. one shown in Fig. 1, implying regional analogy of operations. The authors executed trade studies to estimate how the main vehicle performance characteristics affected the market volume and elasticity of demand. The authors concluded that ten passengers is an appropriate target for thin-haul services to satisfy demand. Considering the current operations, regulations, and an existing study of market size, nine passengers was chosen as design passengers within the Cape Air network for this study.

Table 1 Different airplanes used by various thin-haul operators with passenger configuration and airplane range noted

	Cape Air [17]	Mokulele Airlines [18]	Boutique Air [19]
Airplane	Cessna 402	Cessna Grand Caravan	Pilatus PC-12
Passenger Configuration	9	9	6
Airplane Max Range	920 nmi [20]	964 nmi [21]	1,845 nmi [22]

III. Methodology and Models

With the concept of operations defined, the design methodology is developed next. This discussion is followed by a description of the economic and vehicle models needed to perform the study.

A. Design Framework

The framework is designed to provide a systematic means of evaluating the performance of a vehicle operated in a network of flights. The study objective, a network-optimized design of a hybrid electric vehicle to maximize operating profit, inherently requires models for the network, the vehicle design, and the economics. The integration of these three items forms the backbone of this study. The structure is standard regardless of the type of vehicle being analyzed. Figure 3 shows the basic analysis structure populated with all of the necessary elements for both conventional and hybrid electric vehicles. The elements specific to the hybrid electric vehicle are highlighted in green text for clarity. Each module in this framework is described in the following sections.

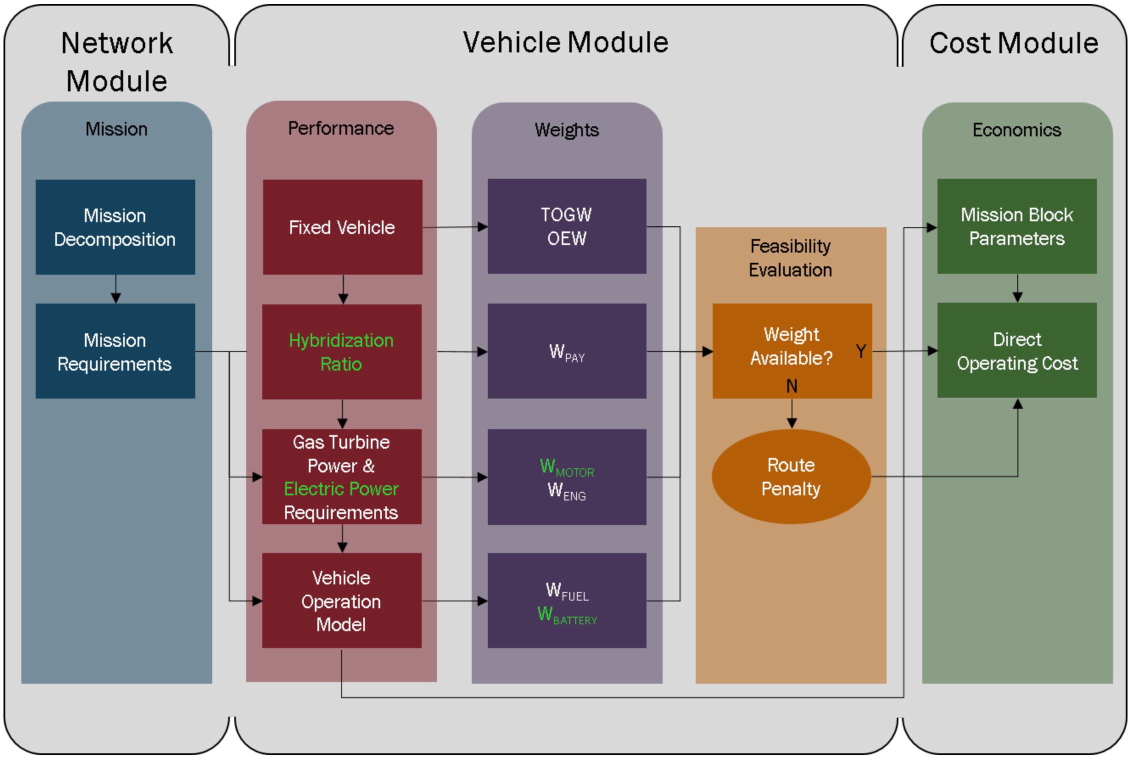

Fig. 3 Framework layout for both conventional and hybrid electric vehicles

B. Network Module

The network module serves as basic mission decomposition and requirements allocation for each route within the network. One week of the Cape Air schedule is used as it encapsulates a realistic implementation of thin-haul operations. Within the mission module, the haversine distance of each route is computed. This distance is then increased by about 28% to account for arrival and departure procedures as well as air traffic management routing inefficiencies which force the flight path to be longer than the great circle distance. In addition, the mission profile and associated cruise altitude are selected to ensure that the airplane flies at least one third of the flight at its cruise altitude. Lastly, the payload associated with each flight is initially set to a full passenger load (9pax at 180lbs/pax). These basic mission requirements are then sent to the vehicle module.

C. Vehicle Module

The vehicle module performs two main tasks: (a) to simulate the mission and (b) to account for all mission-specific power, weight, and block parameters. The vehicle used as a baseline to model a thin-haul operator is a notional Pilatus PC-12. The PC-12 is a state-of-the-art turboprop aircraft that can accommodate up to nine passengers. This vehicle was selected semi-arbitrarily, but the framework developed can handle different baseline vehicle without significant modifications.

1. Conventional Thin-Haul Vehicle

The notional PC-12 model is low-fidelity and simulates the mission in order to generate data regarding the block fuel, time, speed, and distance of a given mission. The data used to generate this model is retrieved from the publicly available Pilatus PC-12 “Just the Facts” document [23] and the vehicle’s Pilot’s Information Manual (PIM) [24]. Data is collected regarding altitude and weight specific indicated airspeed, fuel flow rates, and power required for takeoff, climb, cruise, and landing. This data is used to create parametric regressions that are used subsequently during the optimization. The physical vehicle is "fixed", meaning the physical outer mold line, empty weight, and maximum take-off weight (MTOW) are not modified in order to ensure standard weight- and altitude-based power requirements can be used regardless of the vehicle powertrain system.

First, a weight-based takeoff required power and associated fuel burn are calculated. Then, the model identifies the maximum cruising altitude constrained by the assumptions that the climb and descent phases can account for no more than one-third of the total flight distance while the cruise phase can account for no less than one-third of the flight distance. The climb time is calculated using the PIM recommended value of 160 kts indicated airspeed (IAS) for climb, the mission-constrained maximum climb range, and an average climb rate of 1,494 fpm. The climb fuel required is then estimated from the climb power requirement using a regression created from PIM data at ISA+0 conditions and flaps retracted configuration. The maximum cruising altitude is set to 15,000 ft altitude to avoid pressurization and/or supplemental oxygen requirement for passengers.

The cruise speed and corresponding fuel flow are functions of the cruise altitude and vehicle weight. These two parameters define the cruise power requirement and, therefore, fuel flow via the power-specific fuel consumption (PSFC). The distance that the aircraft cruises is determined by subtracting the distance that the aircraft needs to descend and land from the remaining trip distance. The remaining distance is the descent distance subtracted from the distance remaining after climb. The cruise is executed by calculating the cruise time and cruise fuel burn based on the speed, distance, and fuel flow metrics.

All of these values are tracked with additional time and fuel allocated to taxi operations at airports. This analysis process is coded as a function such that any initial airport-to-airport distance and aircraft takeoff gross weight (TOGW) could be used as inputs to calculate the mission block parameters, enabling its use with the network module.

Referring to Fig. 3, the performance and weights units are fully defined. Feasibility is checked via weight available such that the MTOW of the aircraft is not exceeded with fuel weight being the most variable element. For the conventional PC-12, maximum payload and fuel yield a range of 1124 nmi, much more than any of the thin-haul network routes. As a result, mission feasibility is not violated for any of the Cape Air route using the notional PC-12 aircraft. The mission block parameters are used as inputs into the economics module for computing route-specific operating costs and profits. This module will be discussed in detail later in the paper.

2. Hybrid Thin-Haul Vehicle

As previously mentioned, the hybrid vehicle fits the same framework with added elements or element parameters. This subsection discusses only the features that are different for the hybrid vehicle. The same PC-12 baseline vehicle is used with a modified propulsion system. The powertrain for the hybrid vehicle is a parallel hybrid electric architecture, shown in Fig. 4, adapted from [25]. This architecture uses batteries using a 400 Wh/kg specific energy density, an inverter, an electric motor, and the ancillary cabling required for the rigging of these systems. The simulation of this airplane is slightly different from the simulation of the conventional aircraft model. First, the hybridization ratio, ϕ, is defined as the split of electric power as a fraction of total power, shown in Eqn. 1 with *elec* and *gte* noting electric and gas turbine engine, respectively.

$$\phi = \frac{P_{elec}}{P_{elec} + P_{gte}} \tag{1}$$

Because the original PC-12 outer mold lines and weight are used for the hybrid electric PC-12, the power requirements for each phase of flight are obtained directly from the original PC-12 PIM. The combination of power requirement for each mission phase and the hybridization ratio determines the amount of power coming from each source in the parallel system. The PSFC for the original Pratt & Whitney PT-6A-67P gas turbine system is a function of power required, aircraft weight, and altitude. The PSFC is not modified to account for scaling effects of smaller gas turbines. The weight of the gas turbine is computed using the original PT-6 specific power of 1.56 kW/lb. The max power required for the electric system sizes the weight of the electric motor using a motor specific power of 3.00 kW/lb [26]. The hybridization ratio determines the power required from the electric side. The power required from the electric system for each phase of the mission and the associated time are used to estimate the overall electric energy need. This accounts for the powertrain component efficiencies (noted in Table 2) and the 20% reserve to preserve the battery longevity. This energy is translated into battery weight requirement via a gravimetric battery specific energy density.

Once the motor, engine, battery, and fuel weights are determined in the weight unit, the total vehicle weight is known and can be checked against the available MTOW of the fixed PC-12 vehicle. If the total weight is greater than the PC-12 MTOW, then this route is not feasible. Finally, the mission block parameters from this hybrid vehicle's operation (time, distance, speed, fuel, and energy) are computed and transferred to the economics module for cost analysis.

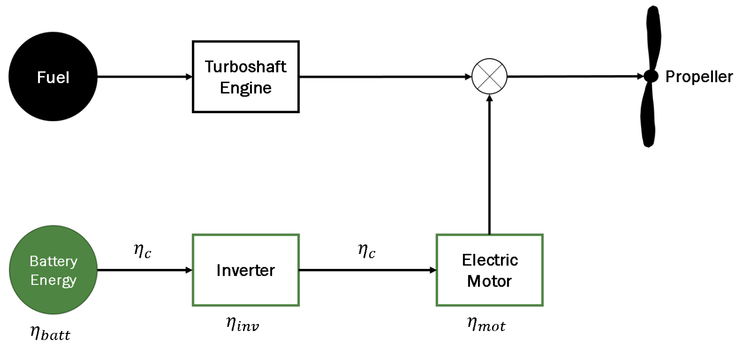

Fig. 4 Parallel hybrid electric powertrain configuration adapted from [25]

Table 2 Hybrid electric powertrain efficiencies

Component	Efficiency
Battery	92% [27]
Inverter	98% [28]
Motor	89% [28]
Cables	98% [29]

D. Economics Module

An electric or hybrid electric vehicle may be technically feasible. Entry into service will however be determined by the economic viability and hinges significantly on the business case supporting development, certification, and operation of the vehicle. The economics module is used to investigate the operating economics of the conventional and hybrid electric aircraft in this study. The economics module employs a parametric version of Roskam's direct operating cost (DOC) build-up methodology as a comprehensive means of quantifying the various sources of expenditures [30]. The model is modified to handle electrified propulsion vehicle. Figure 5 shows all of the elements used in the module with the green elements indicating those added to account for the hybrid electric vehicle features.

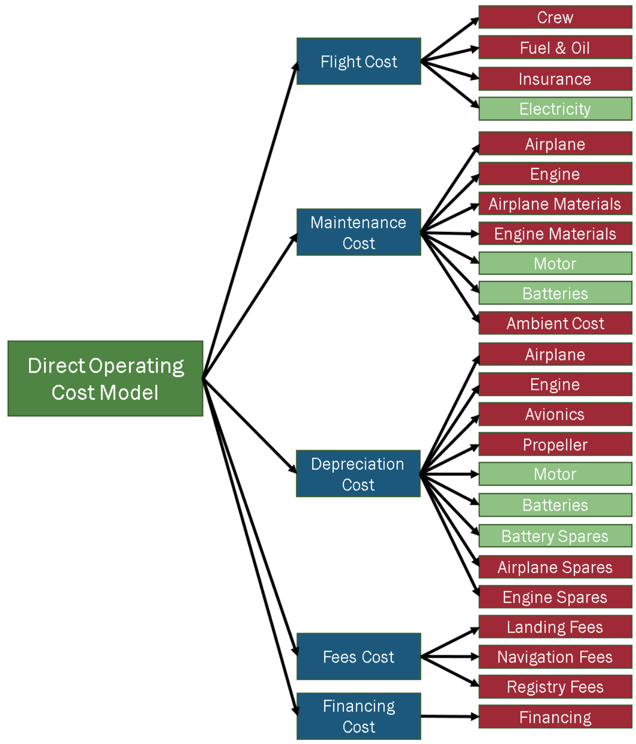

Fig. 5 DOC breakdown for both conventional and hybrid vehicles

1. Conventional Vehicle Direct Operating Cost

Following Roskam's process, the model is created with assumptions and values detailed in Table 6 in the Appendix. The main inputs for each computation of a mission's direct operating cost are the mission block parameters (fuel, time, speed, and distance), which are all computed in the network module or in the vehicle module.

The economics are validated using two different sources of information. The first validation is from Pilatus' "Just the Facts" document for the PC-12 [23]. This document provides estimates for direct operating cost as a function of fuel price. The estimates only include the flight and maintenance costs per nautical mile, but they provide details for up-to-date maintenance labor rates for the aircraft and engine system. These values are used to refine the assumptions used in the DOC model. At $4.00 per gallon, the direct operating cost per hour is $550 for the given reference mission. With the provided block speed of 264 kts, this results in a reference $/nmi direct operating cost of 2.083. This value accounts for maintenance, parts, and labor for the engine, aircraft, and propeller as well as the cost of the fuel used and the payment of a single pilot on the trip. With the same mission, maintenance assumptions and rates, and $4.00 per gallon of fuel, the same subset of operating costs from the model realizes a $/nmi direct operating cost of 2.173, representing a 4.32% difference in the published values and the calculated values from the developed model. This small discrepancy is likely attributed to different assumptions in the cost of the pilot per flight hour. Pilatus does not disclose what they use for that parameter, but it is likely similar to the assumption used herein. This agreement of the numbers indicates that the developed DOC model for this study is acceptably accurate.

The second method of validation is using thin-haul commuter operator data from an operator of Pilatus PC-12 airplanes. Boutique Air, a commuter carrier headquartered in San Francisco, flies a breadth of thin-haul routes across the United States. Data exists regarding the operating economics of the PC-12 on four flights subsidized through the U.S. Essential Air Service program (EAS). The total yearly cost for these routes and operations is divided by the total available seat miles to get the cost per available seat mile ($/nmi). Both sets of validation data are shown in Table 3. The Boutique Air routes represent airport pairs Imperial, CA - Los Angeles, CA, Bar Harbor, ME - Massena, NY, Page, AZ - Phoenix, AZ, and Page, AZ - Salt Lake City, UT. The Boutique Air routes are 181, 321, 243, and 268 nmi for IPL-LAX, BHB-MSS, PGA-PHX, and PGA-SLC, respectively. Running the DOC model for the specific Boutique Air routes shows relative accuracy with moderate discrepancy which is acceptable for the purpose of this study.

Table 3 DOC model validation comparisons

Mission Data	Pilatus PC-12 Published Data ($/nmi)	DOC Model PC-12 Calculated Data ($/nmi)
Out of warranty, 600nmi, 264kts block speed, fuel $4.00/gal	2.083 [23]	2.173

Boutique Air Route	Boutique Air Reported Cost	DOC Model PC-12 for Boutique Air Route ($/nmi/ASM)
IPL-LAX	1.043 [31]	0.881
BHB-MSS	0.849 [32]	0.811
PGA-PHX	0.694 [33]	0.839
PGA-SLC	0.694 [33]	0.830

2. Hybrid Vehicle Direct Operating Cost

After the baseline DOC model is developed and validated, minor changes are needed to modify the conventional vehicle economics to be usable for hybrid electric vehicle. Additional parameters are added to the model, whose values are summarized in Table 7 in the Appendix. The main adaptations to the model include reducing engine-related costs proportional to the gas turbine engine power rating. This scaling affects the gas turbine engine maintenance cost, ambient maintenance cost, engine depreciation, and spare parts depreciation. The other changes includes the energy expenditures and the cost of electricity (value obtained from detailed thin-haul energy cost study by Justin et al. [34]), the motor acquisition cost based on its power rating, and the battery cost based on the concept of lifetime battery throughput [8]. The lifetime energy throughput of the battery is computed using the total capacity and lifetime cycles. The fraction of energy required in a given flight divided by the lifetime energy throughput quantifies how much degradation of the battery occurs for the block time of the flight. That amortization of the total battery cost is included in the direct operating cost for the battery.

E. Method of Evaluation

The over-arching goal of this study is to investigate the economic performance of a hybrid electric vehicle optimized for a thin-haul network compared to a conventional fuel-powered vehicle. An evaluation criterion of direct operating cost makes the most sense if the operations are identical; however, higher levels of hybridization reduce the overall range the vehicle can fly at a given payload level. Beyond certain thresholds of hybridization, some of the routes within the network are no longer flyable. Consequently, operating cost becomes an incomplete metric because it does not give any benefit to the conventional vehicle for its ability to serve the entire network nor does it provide a fair comparison of the two vehicle types. It is surmised that a better metric for comparison is direct operating profit given a specific profit margin beyond operating cost. The comparison is set up such that the benchmark revenue is that of the conventional gas turbine engine vehicle with y% profit margin, assuming 100% load factor. This assumes that the conventional and hybrid electric versions of the PC-12 operate in the same market and that ticket prices are identical (i.e. market driven). The reference direct operating revenue (DOR) and reference direct operating profit (DOP) are given with the following formulations.

$$DOR_{ref} = DOC_{gte} \times (1 + y) \tag{2}$$

$$DOP_{ref} = DOR_{ref} - DOC_{gte} \tag{3}$$

With the reference economics established, the economic performance is analyzed within the network for all levels of hybridization, $\phi \in (0, 100]$ at a given profit margin. The DOC at every level of hybridization is computed and subtracted from the reference DOR to determine the DOP for a given hybridization level. If, at a given level of hybridization, the airplane configuration cannot perform a mission due to range constraint, then the profits and costs from the route are omitted. This omission penalizes the hybrid electric vehicle operation in that the hybrid vehicle foregoes that profit opportunity. The profits associated with each level of hybridization are calculated, with ϕ_i representing any hybridization level and $DOR_{ref_{omit}}$ indicating revenue omitted due to routes not serviced:

$$DOP_{\phi_i} = \left[DOR_{ref} - DOR_{ref_{omit}}\right] - DOC_{\phi_i} \tag{4}$$

With the data from every level of hybridization, a simple, one-dimensional direct search optimization can find the maximum profit level and the corresponding hybridization that generate the maximum profit, shown notionally in the formulation below. Beyond finding the optimal hybridization for the network, investigations into possible trade-offs between payload and range are explored. The following section will discuss the findings of this formulation and evaluation.

$$\begin{aligned} \underset{\phi}{\text{maximize}} \quad & DOP_{\phi_i} \\ \text{subject to} \quad & y = y_i \end{aligned}$$

IV. Implementation

Implementing the models developed in this framework and associated study provides interesting insight into the operation of a hybrid electric vehicle. The first analysis aims at finding the hybridization level that maximizes the network profit. Unfortunately, there is not a single design point answer to this task because the answer depends on the profit margin desired. Figure 6 shows the trend of direct operating profit normalized by the PC-12 direct operating profit for profit margins of 5%, 10%, and 15%, respectively. These profit margins led to different optimal hybridization levels and profit values. Table 4 shows the detail for all of these outfits. From an operational standpoint, this result implies that the configured aircraft can be readily reconfigured with more or less batteries to change the hybridization to better optimize the network profit depending on the specific profit margin goal. It also shows that a lower profit margin can yield more profit, taking advantage of the highly electric configuration. Lastly, a unique feature that Fig. 6 shows clearly is that as the level of hybridization increases, fewer and fewer routes become feasible owing to range restriction (referring to the red line). This explains the Figure's shape for the delta profit trend. Combining the trend of routes serviced with the Cape Air network distribution shown in Fig. 2 explains why the profit curve has a 'sawtooth effect'. As the hybridization ratio increases, some route may become infeasible and the profit suddenly drops. However, because the operating costs of the hybrid electric vehicle are lower, the profit soon increases again as the hybridization ratio keeps increasing until a new route becomes infeasible.

Discrete levels of profit margin only provide a point-design consideration for choosing a hybridization level to maximize DOP. This design space is visualized two ways in Fig. 7, with the contour colors representing profit (2018-$) quantified in the colorbar. The DOP in the left half of this Figure shows the total DOP for the network (DOP-total). The right half of the Figure represents the DOP delta with respect to the baseline conventional propulsion system DOP for every profit margin (DOP-Δ). The DOP-total shows a region of maximum profit on the right boundary depending on the profit margin. This effect displays a non-dominated point of high profit occurring at as low as 6.0% profit margin at 100% hybridization or 10.6% profit margin at 72.1% hybridization. The DOP-Δ has a very interesting appearance. It shows similarity to the charts within Fig. 6: a linear increase of profit into the low-40% range of percent hybrid and then erratic behavior beyond that due to the range feasibility and profit margin-driven effects. The DOP-Δ display shows that the hybrid electric vehicle performs much better economically at low profit margins. At low profit margins, the baseline PC-12 profit (DOP_{ref} from Eqn. 4) is low. Since the hybrid electric aircraft operating cost is substantially lower with the same reference operating profit, the difference between the reference profit and hybrid profit (DOP_{ϕ_i}) becomes larger. Additionally, the low profit margin area does not allow the conventional vehicle to take advantage of its ability to profit greatly on its feasible routes that are infeasible for the hybrid electric vehicle. This result also implies that the operator could fly the hybrid electric aircraft at much lower ticket prices (i.e. reducing revenue) and still make sizable profits by simply taking advantage of the low direct operating cost of the hybrid electric operation.

Table 4 Optimal hybridization ratio and associated profit for different profit margins

Profit Margin	Optimal Hybridization Ratio	Profit Compared to Baseline
5%	96%	$324,000
10%	70%	$288,000
15%	52%	$278,000

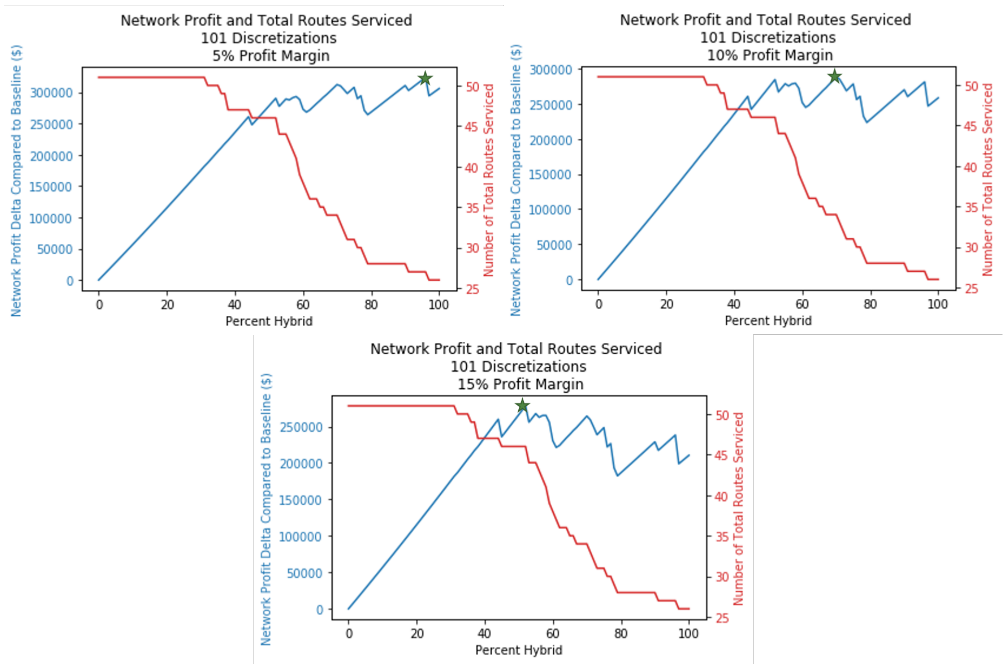

Fig. 6 Hybrid electric network profit normalized to baseline for different profit margins

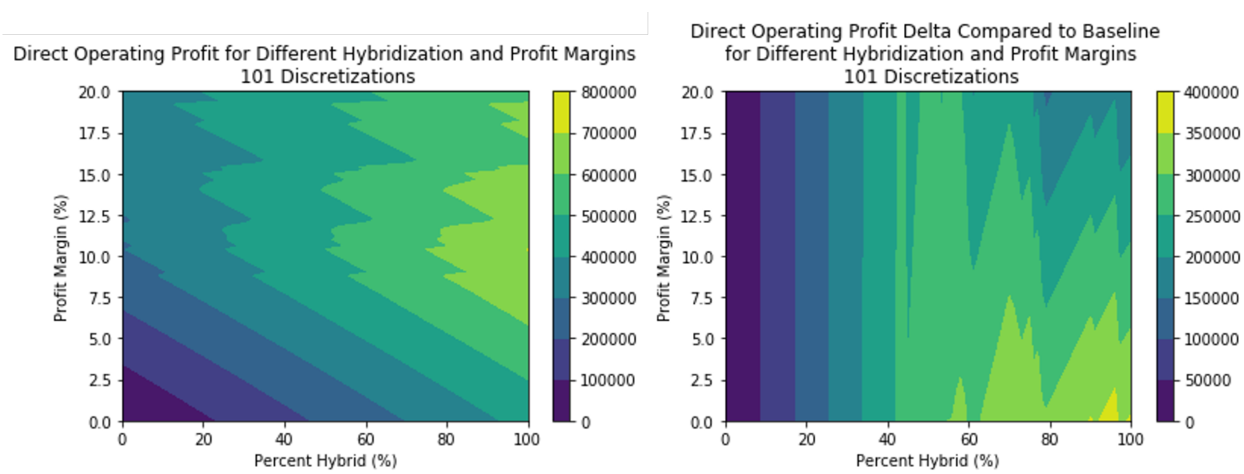

Fig. 7 Contour plot of network direct operating profit for an array of hybridization levels and profit margins

A. Trade Studies

An exploration is performed next to understand the impact of swapping payload for range at different levels of hybridization. Additionally, different levels of battery technology via battery specific energy density are considered.

These trade studies are conducted to investigate characteristics of a hybrid electric system that contribute to its uniqueness and potential marketability for future thin-haul operations. Simply removing payload without adding extra energy source does not change the hybrid electric vehicle feasible range. The fuel flow data gathered from the PIM shows a system insensitivity to weight because the throttle does not change in cruise configuration even if weight changes. If this payload is traded for range by adding modular battery weight in the place of a passenger's weight, then a different result is realized. Volume constraints are neglected for the sake of this exploration. Table 5 shows the delineation for 10% intervals of hybridization. This table highlights that added electric energy storage capacity has less and less impact as the propulsion system becomes more electric. This phenomenon is intuitive as each passenger's weight replaced by a battery may provide the same amount of energy, but the resulting higher hybridization implies that this amount of energy will be used more rapidly due to the higher electric power requirement. Consequently, this yields less range augmentation. Forcing the reduction of the load factor for the sake of increasing the range of the vehicle can enable the vehicle to fulfil more routes within the network. This compromise creates the need to charge the remaining ticketed passengers more to overcome the loss of revenue from the removed payload capacity or to operate that route with lower revenues. That solution actively works against the desire to maximize operating profit. However, dropping routes may also have adverse network-wide impacts when connecting passengers on these dropped routes are feeding other flights within the network.

Table 5 Passenger payload for range trade-off by adding battery for 10% levels of hybridization

# Pax	Hybridization Level (400 Wh/kg)											
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	
9	1124	580	388	289	229	189	160	138	120	107	95	**Range: nmi**
8	1207	624	417	312	247	204	173	149	131	116	104	
7	1289	667	447	334	265	219	186	161	141	125	112	
6	1372	711	476	357	284	234	199	172	152	135	121	
5	1455	754	506	379	302	250	212	184	162	144	130	
4	1537	797	536	401	320	265	225	196	172	154	138	
3	1620	841	565	424	338	280	239	207	183	163	147	
2	1702	884	595	446	356	295	252	219	193	172	155	
1	1785	928	624	469	374	311	265	230	203	182	164	
0	1868	971	654	491	392	326	278	242	214	191	173	
nmi/pax	82.67	43.44	29.56	22.44	18.11	15.22	13.11	11.56	10.44	9.33	8.67	

Battery specific energy density of 400 Wh/kg is quite optimistic at the pack level even if battery technology capabilities keep improving year over year. Exploring the battery energy density design space, Fig. 8 shows contours of direct operating cost in ($\$/nmi$) for an array of battery energy densities and different levels of hybridization for three different ranges. The three ranges are representative of short-, mid-, and long-distance thin-haul route within the network (27nmi, 110 nmi, and 185nmi, respectively). The contours clearly show the combinations of hybridization and energy density that yield infeasible routes. The contour colors also show the rapid reduction in direct operating cost for longer-ranged flights in the network with the caveat of reduced system feasibility at longer ranges. Finally, the Figure shows that higher levels of battery specific energy density enable longer flights at a given hybridization level or for reduced operating cost at a given range. A positive attribute of hybrid systems is that the batteries can be modular. If new battery technology antiquates operating batteries, then old batteries can be removed and new batteries can be installed with little effort or vehicle modification, unlike re-engining an airplane with a new more efficient gas turbine engine.

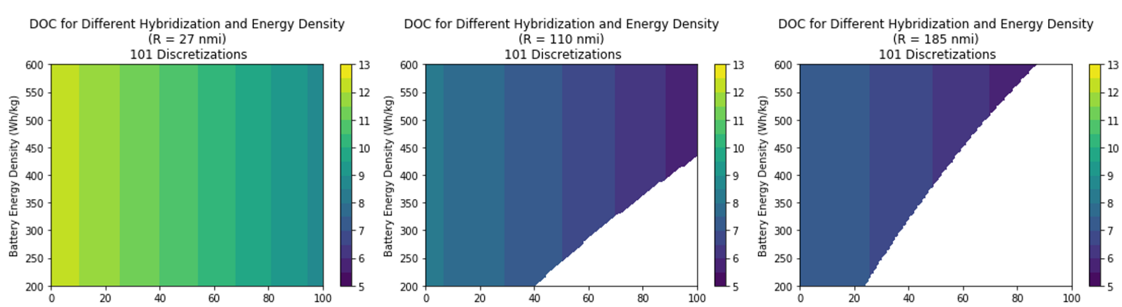

Fig. 8 Battery energy density feasibility space and direct operating cost for three different ranges

V. Conclusion

This study aims to optimize a representative hybrid electric aircraft to maximize the direct operating profit of the operation in a thin-haul network. In order to execute this task, a modelling and simulation framework with network, vehicle, and economics modules is developed to operate the vehicle in the network and to quantify the vehicle's economic performance within said network. The hybrid electric aircraft is based on and compared to a benchmark Pilatus PC-12 turboprop aircraft. It uses the existing aerodynamics, performance, and operating empty weight of the PC-12 with a modified parallel hybrid electric powertrain architecture. The hybridization ratio (ratio of electric power to total power) is optimized and compared to the operating economics of the conventional PC-12 to determine its ability to economically out-perform the conventional configuration. In this investigation, the study found that at profit margins of 5%, 10%, and 15%, the hybrid electric vehicle was optimized at hybridization levels of 96%, 70%, and 52% yielding in increased weekly network profit of $324,000, $288,000, and $278,000, respectively. The lower profit margin yields more profit with respect to the baseline because it does not allow the conventional vehicle to take advantage of earning significant profit on longer routes that the hybrid electric aircraft cannot fly. The lower profit margin exploits the drastic reduction in direct operating cost for the majority of routes in the Cape Air network that are < 100nmi.

Additionally, trade studies are performed to show the opportunity available to increase the aircraft range at different hybridization levels by swapping payload (passenger weight) with propulsive energy (batteries). This consideration shows a diminishing range return for payload-energy swaps as hybridization level increases. It also demonstrates that the infrequent routes on the top-end range in the network might not be worth pursuing. Lastly, changes in the battery energy density assumption are investigated to see how the direct operating cost and feasibility are impacted. These trades reveal that higher energy density dramatically decreases range-specific DOC, and it also enables significant feasibility enhancements for long-range thin-haul operations. The long-range thin-haul operations with high energy density can store larger amounts of energy on-board without violating the MTOW requirements of the retrofitted hybrid electric vehicle.

A. Future Work

The study presented in this paper tries to address a very broad objective requiring several modelling assumptions that might be relaxed in the future. Future work derived from this study can include increasing model fidelity for the powertrain and vehicle to capture more rigorously the intricacies of a hybrid electric powertrain and its integration into the aircraft. Additionally, the PC-12 retrofit with a hybrid electric powertrain significantly limits the vehicle-design attributes that an electrified propulsion can take advantage of in its configuration, namely distributed electric propulsion. A "clean-sheet" airplane could be designed specifically to optimize the network performance in a way that the retrofitted vehicle is restricted.

Appendix

Table 6 Conventional vehicle direct operating cost variables, descriptions, units, and baseline values for PC-12

Variable	Description	Units	PC-12 Value
Num_Captains	Number of captains operating the aircraft	[people]	1
Num_First_Officers	Number of first officers operating the aircraft	[people]	0
Cost_Factor	Factor accounting for overhead related to the pilots	[–]	0.26
Block_Speed	Gate-to-gate speed	[kts]	1*
Captain_Salary	Salary of captains	[$]	75,000
First_Officer_Salary	Salary of first officers	[$]	35,000
Captain_FlightHours_Year	Number of flight hours per year for a captain	[hrs/yr]	900

*This is a placeholder number that will change per mission

FirstOfficer_FlightHours_Year	Number of flight hours per year for a first officer	[hrs/yr]	900
Travel_Expense_Factor	Expense factor accounting for crew accommodations during operation	[–]	13.52
Block_Fuel	Gate-to-gate fuel burn	[lbs]	1*
Block_Distance	Gate-to-gate distance	[nmi]	1*
Fuel_Price	Price of fuel	[$/gal]	4.00
Fuel_Density	Density of fuel	[lbs/gal]	6.7
Num_Engines	Number of Engines	[engines]	1
Block_Time	Gate-to-gate time	[hrs]	1*
Price_Oil_Lubricants	Price of oil and lubricants	[$/gal]	10
Oil_Density	Density of oil and lubricants	[lb/gal]	7.74
Hull_Insurance_Rate	Rate of insurance rate for aircraft hull	[$/$/airplane/yr]	0.01
Ac_Market_Price	Market price of the aircraft	[$]	4,500,000
Annual_BlockHour_Util	Annual block hour utilization	[hrs/yr]	1,500
Ac_MtxHours_FlightHour	Aircraft maintenance hours per flight hour	[–]	0.68
Ac_MtxLaborRate	Aircraft maintenance labor rates	[$/hr]	105
Eng_MtxHours_BlockHour	Engine maintenance hours per flight hour	[–]	0.68
Eng_MtxLaborRate	Engine maintenance labor rates	[$/hr]	131.65
Ac_Mtx_MatCost_BlockHour	Aircraft maintenance material cost per block hour	[$/hr]	125
Eng_Mtx_MatCost_BlockHour	Engine maintenance material cost per block hour	[$/hr]	40
Labor_Overhead_Factor	Labor overhead distribution factor	[–]	1.00
Mat_Overhead_Factor	Material overhead distribution factor	[–]	0.40
Eng_Price	Price per aircraft engine	[$]	750,000
Num_Prop	Number of propellers	[prop.]	1
Prop_Price	Price per propeller	[$]	50,000
AvSys_Price	Price of avionics system	[$]	40,000
Ac_Depr_Factor	Aircraft depreciation factor depending on perceived resale value of item	[–]	0.90
Ac_Depr_Period	Aircraft depreciation period	[yrs]	15
Eng_Depr_Factor	Engine depreciation factor depending on perceived resale value of item	[–]	0.90
Eng_Depr_Period	Engine depreciation period	[yrs]	10
Prop_Depr_Factor	Propeller depreciation factor depending on perceived resale value of item	[–]	0.90
Prop_Depr_Period	Propeller depreciation period	[yrs]	10
AvSys_Depr_Factor	Avionics system depreciation factor depending on perceived resale value of item	[–]	1.00
AvSys_Depr_Period	Avionics system depreciation period	[yrs]	10

Ac_SpareParts_Depr_Factor	Aircraft spare parts depreciation factor depending on perceived resale value of item	[–]	0.90
Ac_SpareParts_Factor	Aircraft spare parts factor relating cost relating spare parts cost to cost of airplane minus engines	[–]	0.10
Ac_SpareParts_Depr_Period	Aircraft spare parts depreciation period	[yrs]	15
Eng_SpareParts_Factor	Engine spare parts factor relating spare parts cost to cost of one engine	[–]	0.50
Eng_SpareParts_Price_Factor	Engine spare parts price factor relating cost of spare parts to cost of part of a fully assembled engine	[–]	1.50
Eng_SpareParts_Depr_Factor	Engine spare parts depreciation factor depending on perceived resale value of item	[–]	0.90
Eng_SpareParts_Depr_Period	Engine spare parts depreciation period	[yrs]	10
TOGW	Takeoff gross weight	[lbs]	1*
NavFee	Navigation fee	[$]	0

Table 7 Additional direct operating cost variables and associated information for hybrid electric vehicle

Variable	Description	Units	Hybrid Thin-Haul Value
Percent_Hybrid	Hybridization level, % electric power	[–]	1 †
Block_Electric	Gate-to-gate electricity usage	[kWh]	1†
Electric_Price	Cost of electric energy	[$/kW]	0.12
Motor_Spec_Cost	Power specific motor cost	[$/kW]	135
Electric_Power	Electric power rating for motor	[kW]	1†
Motor_Life_Hours	Total hours of motor life before replacement	[hrs]	10,000
Total_Battery_Capacity_wReserves	Total battery energy required for block and reserve	[kWh]	1†
Num_Cycles	Number of battery cycles in battery life	[cycle]	1500
Spec_Battery_Cost	Cost of battery per unit energy	[$/kWh]	100

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† This is a placeholder number that will change per mission

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